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Mars Pathfinder Microrover

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Abstract

When the Mars Pathfinder (MPF) spacecraft lands on Mars, the. Microrover Flight Experiment (MFEX) will be deployed perform its mission to conduct technology experiments verifying the engineering design, to deploy an alpha proton x-ray spectrometer (APXS) to measure elemental properties of rocks and soil, and to image the MPF lander. In accomplishing this mission the MFEX rover must determine a safe path to goal locations traversing over a poorly known Martian surface. The rover does this mission with a capable mobile platform executing on-board autonomous functions of navigation and hazard avoidance. In this paper we describe the rover, its operational environment and the implementation of the on-board autonomous functions.

On July 4, 1997 the Mars Pathfinder (MPF) spacecraft enters the Martian atmosphere, is braked successively by an aeroshell, parachute, rockets and airbags. Once on the surface the lander (the remaining portion of the spacecraft) rights itself by retracting airbags and deploying petals. On the petals arc solar panels which will power the lander for the remainder of its mission. On onc of these petals is the Microrover Flight Experiment (MFEX), the first roving vehicle on Mars.

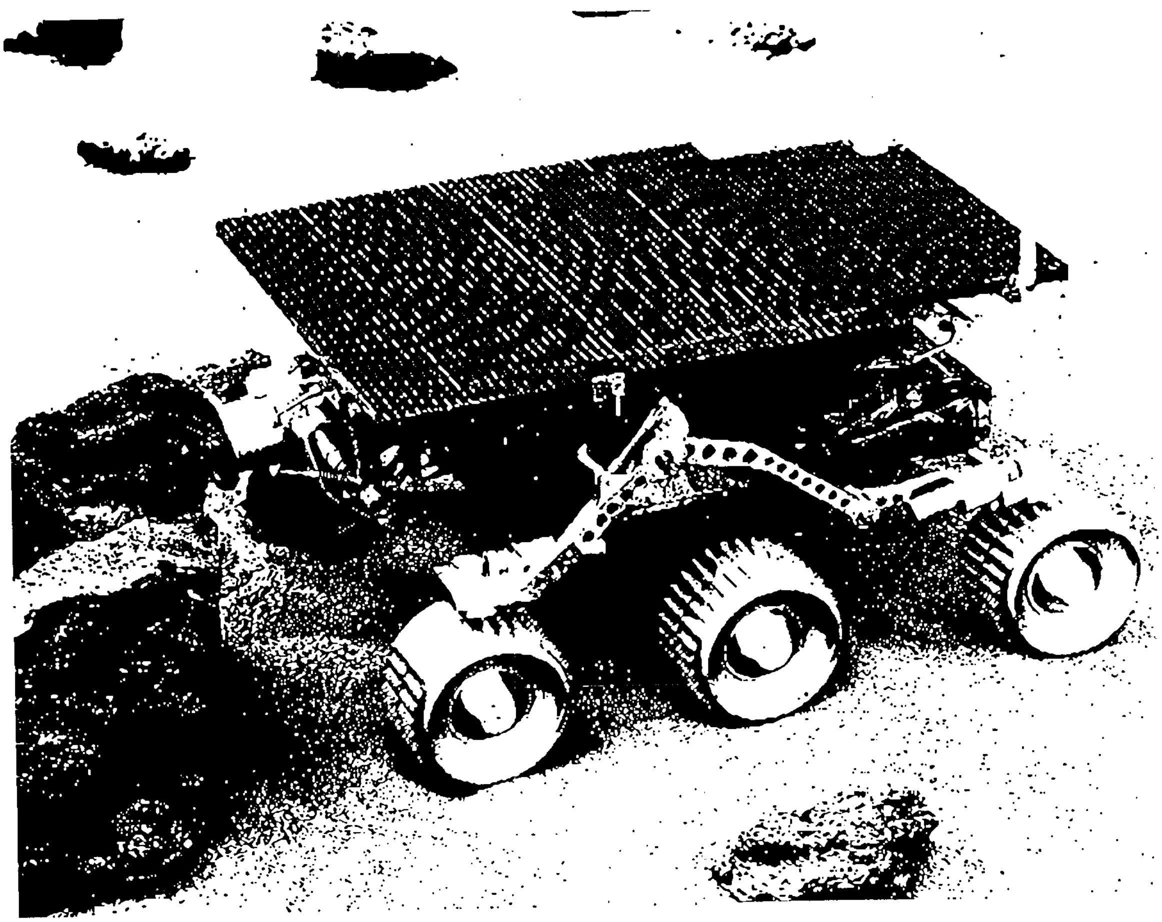
The MFEX is a NASA Office of Space Access and Technology flight experiment of autonomous mobile vehicle technologies, whose primar y mission is to determine microrover performance in the poorly understood planetary terrain of Mars. After landing, the microrover is deployed from the lander and begins a nominal 7 sol (= Martian day) mission to conduct technology experiments such as determine wheel-soil interactions, navigate, traverse and avoid hazards, and gather data which characterizes the engineering capability of the vehicle (thermal control, power generation performance, communication, etc.). In addition, the microrover carries an alpha proton x-ray spect rometer (APXS) which when deployed on rocks and soil will determine element composition. Lastly, to enhance the engineering data return of the MPF mission, the microrover will image the lander to assist in status/damage assessment.

Duc to the (nominally) once pcr sol opportunity for communication with the earth, MFEX must carry out its mission in a form of supervised autonomous control in which, for example, goal locations are commanded and the vehicle traverses in an attempt to reach these locations. This paper describes the planned on-board capabilities of the MFEX rover which implements this form of supervised autonomous control.

1. Description of the MFEX rover.

(See Figure) The MFEX rover is a 6-wheeled vehicle of a rocker bogie design which allows the traverse of obstacles a wheel diameter (13cm) in size. Each wheel is independentl y actuated and geared (2000:1) providing superior climbing capability in soft sand. The front and rear wheels arc independently steerable, providing the capability for the vehicle to turn in place (a 74cm turning diameter). The vehicle has a top speed of 0.4m/min.

The rover is powered by a 0.22sqm solar panel comprised of 13 strings of 18, 5.5mil GaAs cells each. The solar panel is backed up by 9 $LiSOCL_2$ 1)-cc]] sized primary batteries, providing up to 150W-hr. This combined panel/batteries system allows rover power users to draw up to 30W of peak power (mid-sol) while the peak panel production is 1 SW (mid-sol at the 19.5deg north lattitude of the proposed Mars landing site). The normal driving power requirement for the rover is 10W.



Rover components not designed to survive ambient Mars temperatures (- 11 0degC during a Martian night) are contained in the warm electronics box (WEB). The WEB is insulated, coated with high and low emissivity paints, and heated with a combinat ion of 3, 1 W RHU's, resistive heating under computer control during the day and waste heat produced by the electronics. This design allows the WEB to maintain components between -40degC and +40degC during a sol.

Control is provided by an integrated set of computing and power distribution electronics. The computer is an 80C85 rated at 100Kips which uses, in a 16Kbyte page swapping fashion, 176Kbytes of PROM and 576 Kbytes of RAM. The computer performs I/O to some 90 sensor channels and services such devices as the cameras, modem, motors and experiment electronics.

Vehicle motion control is accomplished through the on/off switching of the drive or steering motors. An average of motor encoder (drive) or potentiometer (steering) readings determines when to switch off the motors. When motors are off, the computer conducts a proximity and hazard detection function, using its laser striping and camera system to determine the presence of obstacles in its path. The vehicle is steered autonomously to avoid obstacles but continues to achieve the commanded goal location. While stopped, the computer also updates its measurement of distance traveled and heading using the averaged odomctry and on-board gyro. This provides an estimate of progress to the goal location.

Command and telemetry is provided by modems on the rover and lander. The rover is the link commander of this 1/2 duplex, UHF system. During the day, the rover regularly requests transmission of any commands sent from earth and stored on the lander. When commands are not available, the rover transmits any telemetry collected during the last interval between communication sessions. The telemetry received by the lander from the rover is stored and forwarded to the earth as any lander telemetry. In addition, this communication system is used to provide a 'heartbeat' signal during vehicle driving. While stopped the rover sends a signal to the lander. Once acknowledged by the lander, the rover proceeds to the next stopping point along its traverse.

Communication between the lander and earth is provided twice each sol for two hours during each period. The command and telemetry functions of the rover are designed to work within these communicant ion constraints. Commands are general 1 y designed at a 'high-level' (for example, 'go_to_waypoint' where a waypoint is a coordinate in the terrain referenced to the location of the lander) and are collected into a sequence for execution by the rover. The sequence is sufficient to carry out the mission functions of the rover on the given sol of issuance. Telemetry is collected during the execution of these commands and is transmitted to the lander. The lander stores this data and forwards the information to earth during a communication opportunity (perhaps not until the next sol).

Commands for the rover are generated and analysis of telemetry is performed at the rover control station, a silicon graphics workstation which is a part of the MPF ground control operation. At the end of each sol of rover traverse, the camera system on the lander takes a stereo image of the vehicle in the terrain. Those images, portions of a terrain panorama and supporting images from the rover cameras are displayed at the control station. The operator is able to designate on the display points in the terrain which will serve as goal locations for the rover traverse. The coordinates of these points arc transfered into a file containing the commands for execution by the rover on the next sol. In addition, the operator can use a model which, when overlayed on the image of the vehicle, measures the location and heading of the vehicle. This information is also transfered into the command file to be sent to the rover on the next sol to correct any navigation errors. This command file is incorporated into the lander command stream and is sent by the MPF ground control to the lander, earmarked for transmission to the rover.

2. Autonomous Functions during traverses

In achieving its mission, the MFEX rover must traverse to locations commanded once per sol from ground control. In order to accomplish a traverse the rover must determine:

- where to go (based on where it is),
- drive to the location,
- avoid hazards in route, and
- decide along the way if it is making sufficient progress to get to the location in the required time.

For this last item, time is determined sufficient to allow (with margin) the lander camera to image the rover in the terrain and, since this image becomes the planning image for the next sol of rover operation, to ensure that the image can be communicated to earth on the same sol as the image is taken. The rover must perform a series of autonomous functions in order to accomplish such traverse given these constraints. The following subsections highlight several of these functions.

a. Position and heading determination

Once each sol the rover can receive an update to its location relative to the lander from the ground controller. This 'localization' is an x,y position relative to a center coordinate on the lander transformed from coordinates determined on the image plane of the lander camera. The operator sitting at the control station need only move the cursor on the image displayed at his terminal to determine where the rover is located in the terrain or designate a new location to send the rover (via a 'go_to_waypoint' command which is parameterized by these coordinates). The orientation of the 3-d cursor gives the heading which is a part of the localization function. By reorienting the cursor, the operator can designate a new orientation to send the rover (via a 'turn' command which is parameterized by this orientation).

During a traverse, the rover must regularly and autonomously update its position relative to the lander to determine (at a minimum) if it has reached the objective of its traverse. This update is accomplished through the processing of a combination of sensor measurements taken during the traverse. During execution of a 'go_to_waypoint' command, the vehicle odometer is updated using the encoder reading on the wheel actuators. A single encoder count is registered each time the motor shaft of the actuator completes a revolution. Given the gear ratio in the actuator, 2000 counts are registered on a single wheel revolution, The counts accumulated on each of the six wheels are averaged to determine an average odometry update. This update is performed while the vehicle is stopped, which occurs about once each wheel radius (6.5cm) of length traversed.

The update is also tested against the meaurement from the gyro taken during the traverse. The gyro, mounted to align its input axis to the direction of forward motion by the vehicle, provides sensing of the distance traversed. The difference between this gyro-based measurement and the average odometry is a measure of the amount of slip incurred during the traverse. This information (average odometry and gyro measurement) are provided in telemetry for evaluation of both the position determination process and the success of the traverse.

Another part of a traverse occurs as the rover turns. Tile command to 'turn' is parametrized with either a heading relative to a reference vector in the lander based coordinate system or to an angle relative to the current rover heading. From the current heading, a new heading is derived based on the commanded parameter. To achieve this heading, the four outside wheels are cocked to the 'steer-in-place' orientation. This is accomplished by driving the steering actuators to the appropriate position as measured by the potentiometers on each actuator. The vehicle is then driven until the commanded orientation is achieved as measured from the gyro. Once the orientation is achieved, the integrated angular measurement from the gyro is used to update the vehicle heading reference.

b. Hazard detection and avoidance

Commands to traverse are generated at the operator console based on an evaluation of images taken from the lander of the terrain. However, as the rover moves from the vicinity of the lander the resolution of terrain features declines. The rover must determine a safe path for traverse.

An on-board hazard detection function provides a means for evaluating the terrain in front of the rover for safe traverse. The rover is equipped with a pair of cameras and an array of 5 laser light stripers. When a laser is powered, a plane of light is cast illuminating a part of the region in front of the vehicle. The cameras, with optics tuned to the light of the lasers, image the illuminated terrain. Selected horizontal lines of the image are read and processed. Displacement from a straight line cutting across these horizontal lines indicates the presence of an obstacle in the path. Each laser is powered in turn and the images in each camera processed. The results arc correlated to develop a sparse map of obstacle distances and heights in front of the vehicle. The map is then assessed against the following criteria for vehicle traversibility :

were scan line intersections missing indicating possible hole or cliff

are the differences between lowest and highest height values above a threshold (not greater than a 30deg slope) indicating excessive slope

are the differences between two adjacent height values above a threshold (not greater than an wheel diameter) indicating a step-type hazard

is there clearance for the vehicle to turn in place between adjacent obstacles

If any criteria fail, a hazard is declared.

If a hazard is detected, the rover then autonomously turns to the left if the hazard is to the right of the center of the image. The rover turns to the right otherwise. The usual position estimation update is performed (as described above for the command 'turn') and the hazard detection is repeated. The heading of the rover prior to the first autonomous hazard avoidance turn is stored as the destination heading (i.e., this heading may be the heading of a commanded 'turn' or the implicit heading of the rover in execution of a 'go_to_waypoint' command). The heading and position of the obstacle which caused the autonomous hazard avoidance turn is also stored as the avoidance heading and position. Once the hazard detection function determines a clear traverse is possible, the rover drives forward updating its position estimate (as described above for the command 'go_to_waypoint') until the obstacle is past (i.e., as determined from the current estimated rover heading and position compared to the avoidance heading and position). Once the obstacle is past, the destination heading becomes the goal of an autonomous turn. The rover is oriented to the destination heading. If this hazard avoidance occured in the midst of the execution of a 'turn' command, the next command in the sequence of traverse commands is executed, If this occured during a 'go_to_waypoint' command, the rover is driven to the achieve the goal coordinates, the objective of that command.

Other tests arc conducted as part of the hazard detection function. The on-board accelerometers (one aligned to each axis of the vehicle) serve as a set of inclinometers, measuring the angle to the local gravity vector. An angle measurement beyond a threshold (not greater than a 30deg slope) represents an excessive slope condition as if detected by the laser and camera system. The reaction of the rover is as described above.

The on-board bogie and differential potentiometers combine to measure the position of the wheels relative to the chassis. As the rover traverses, these measurements arc used to determine sinkage. Beyond a threshold (nominally a wheel diameter), a change in terrain below the vehicle causes the vehicle to back-up, declare a hazard at that location and proceed as described above.

Lastly, the difference between a gyro-based measurement of distance traversed and the average odometry, developed from the wheel encode]s, is a measure of the amount of slip. Excessive slip beyond a threshold (nominally, a wheel radius in length) causes the rover to back-up, declare a slip hazard at the location and proceed with hazard avoidance.

The hazard detection function, which includes the proximity detection by the cameras and lasers and the other tests of slope, sink and slip anomalies, is conducted once every wheel radius in length of traverse or before any turn. Power management concerns dictate that cameras and lasers cannot be used while the vehicle is moving. Hence, the rover exhibits a 'start-stop' behavior during traverses, with the vehicle moving a wheel radius then stopping to perform hazard detection/avoidance functions and update its position and heading, estimates. The distance traveled between hazard detection/avoidance activities is a programmable parameter, which can be set by the operator. Depending on the assessment of the terrain at the console, the operator can change the distance parameter, lengthening the distance if obstacle-free or otherwise traversible terrain is present.

c. Find_rock

The hazard detection function of the rover can also be used to locate an obstacle such as a rock in support of the science objective of the mission, the conduct of an APXS experiment. Normally, the operator would designate a series of traverse commands which (if executed successfully) would result in placing the rover in position to deploy the APXS instrument and drive backward placing the instrument on a rock. However, in obstacle strewn terrain, the position estimation function of the rover can degrade significantly requiring that the deployment of the APXS span two sols (at least), with an intermediate correction from the ground operator.

The 'find_rock' command allows the hazard detection function to be used in reverse. A spiral search pattern is traversed by the rover with the search parameter being a step-type hazard (two adjacent height values above a threshold in the obstacle map). When found, the rover centers on the hazard, turns around, and can deploy the APXS instrument and drive back ward until the instrument is on the 'rock'. When the operator can intervene (communication with the earth is possible), the rover will stop before deployment of the APXS instrument, allowing the operator to verify that a rock has indeed been found, that an APXS experiment should be performed and that the deployment can proceed without additional correction in the vehicle position or orientation.

d. Time-out

Each 'go_to_waypoint' command in a traverse is parametrized with a time value for execut ion. This time accounts not only for the nominal execution oft he path to the commanded position but also for the time associated with corrections to the path due to hazard avoidance activities. The operator can select the amount of time based on an assessment of the terrain and the aggregate time required before the taking of the end-of-sol planning picture from the lander and the closing of the communication window to earth. When the command 'times-out' the rover stops, does not execute furt her t raverse commands in the operative sequence, and sends telemetry.

e. Power management

Rover command implicitly contain certain assumptions about power utilization. As part of the sol's sequence of commands, the rover will 'wait' until a given time of day for execution based on models of available solar power. Due to the limited available power sources on board (solar power with primary battery backup), the rover also checks automat icall y for available power before executing a command. An on-board algorithm estimates the power available from the solar panel based on measurements taken from a temperat urc sensor, a shorted solar cell and an open solar cell mounted on the panel. Once calculated, the power available is compared against the appropriate entry in a table which gives power utilization values for each command. The command is not executed until adequate power is available from the solar panel. This test can be overriden if batteries are allowed to backup the panel for the devices used during the execution of the command.

3. Other autonomous functions

At other times during the MFEX mission autonomous functions on-board the rover conduct routine monitoring, provide device fault protection and allow accomplishment of a mission in the presence of a contingency condition such as loss of communication with earth.

a. Thermal management

Much of the thermal control of the rover is performed passively through the vehicle design. Thermally sensitive components and electronics are housed in the Warm Electronics Box (WEB). The WEB is an insulated box which, with nominal Mars surface environment conditions, maintains internal components between -40degC and +40degC.

To provide margin in case of off-nominal conditions an array of resist ive heaters is attached to the largest thermal mass within the WEB, the batteries. During the day, the rover samples temperature sensors within the WEB and checks to ensure that electronics distributed throughout the WEB have not become too hot. If not, power is supplied to the heater array. During the day, the heaters arc turned off if power is required for traversing or other power intensive activities. When idle or otherwise not executing commands, the heater array is turned on.

b. Device checks

The rover maintains a ready status of its nearly 90 devices (ranging from actuators to current sensors). During the execution of commands and periodically through the conduct of health check, device readiness is assessed. Repeated failures such as motor short, anomalous temperature reading, etc. result in a device being declared 'not available for use'. This condition on a given device can be commanded by the operator if diagnosis of command execution anomalies or health check telemetry provides evidence of failure.

c. Contingency sequences

As a means of accomplishing its mission in case of a loss of commands from earth, the rover maintains contingency sequences in memory. These command sequences allow the rover to perform elements of its mission such as soil mechanics experiments, APXS sampling of rocks, and navigation in view of the lander cameras. The rover drives to the vicinity of the lander and begins executing the contingency commands, transmitting engineering data during execution. If downlink telemetry to the lander is available, this data will be received and stored by the lander for subsequent transmission to earth. If the downlink is not available, additional lander imaging during (and after) execution of the commands can be used to return information about the performance of the rover. The rover maintains a 36hr timer on board. Absence of commands for more than 36hrs causes the Contingency sequence to be initiated.

The sequence described above applies after the rover has left the lander. Other sequences arc invoked which allow autonomous deployment from the lander once the rover is released. Absence of commands resulting in the time-out of the 36hr timer causes this deployment to take place.

4. Summary

In order to achieve its mission objectives, the MFEX rover executes a sequence of commands transmitted once per sol from ground control. Given the uncertainty in knowledge of the Martian terrain, the commands arc given in the form of 'high-level' commands such as 'go_to_waypoint' which require the rover to autonomously avoid hazards and determine whether the objective of the command has been achieved. The on-board navigation and hazard avoidance functions provide this capability. In addition, monitoring of device states and resource utilization allow the rover to adapt execution of these commands in the presence of component failure and resource availability to accomplish its mission.

Acknowledgement

The research describe in this paper was carried out by tile Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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